X-560-71-309

PREPRINT

NASA TM X-65684

ERTS IMAGE BOUNDARIES

GERALD J. GREBOWSKY

JULY 1971

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-560-71-309

ERTS IMAGE BOUNDARIES

Gerald J. Grebowsky

July 1971

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

ERTS IMAGE BOUNDARIES

Gerald J. Grebowsky

ABSTRACT

Since the scanning of a ground scene is accomplished by different techniques in the Earth Resources Technology Satellite (ERTS) Multi-Spectral Scanner (MSS) and Return Beam Vidicon (RBV) systems, the boundaries of an MSS image and an RBV image will not be the same. The study discussed in this report was intended to define the image boundaries and the changes in these boundaries due to variations in the position and orientation of the ERTS spacecraft. Quantitative results are derived for the nominal case with perfect attitude control and for expected worst case effects of attitude variations.

PRECEDING PAGE BLANK NOT FILMED

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (continued)

TABLES

FRTS IMAGE BOUNDARIES

SENSOR SYSTEMS

The Earth Resources Technology Satellite (ERTS) will have two distinctly different types of image sensor systems - the Return Beam Vidicon (RBV) and the Multi-Spectral Scanner (MSS).

The RBV system consists of three separate cameras (one for each spectral band: 0.475-0.575, 0.580-0.680, and 0.690-0.830 microns) with separate optics and shutters. All three shutters are operated simultaneously at 25 second intervals with a nominal exposure time of 12 milliseconds. A complete scene within a square 16.22 degrees across the diagonal (as seen from the spacecraft) is detected and stored on the photoconductor in an RBV camera. The square RBV image is nominally oriented with its vertical axis coincident with the orbit plane and is scanned to produce an analogue video signal which is telemetered to ground receiving sites. The direction of scan is from right to left when facing in the direction of spacecraft motion and successive scan lines advance in the direction of spacecraft motion. Roughly, this corresponds to a west to east scan as the satellite moves from north to south.

The MSS system is a point scanning system consisting of a rotating mirror mechanism and a lens system which focuses light onto four separate detector arrays (one for each spectral band: 0.5-0.6, 0.6-0.7, 0.7-0.8, and 0.8-1.1 micron). Each detector array has six detectors which produce six contiguous scan lines as the mirror scans across the satellite track. The instantaneous field of view (IFOV) of each detector is 0.086 milliradian which yields a square IFOV of 78.9 by 78.9 meters (259 by 259 feet) when the satellite altitude is 918.6 km (496 nautical miles). A digital video signal is produced by sampling the detector outputs as the mirror rotates. As in the RBV, scanning is from right to left when facing in the direction of spacecraft motion and the mirror scan time (73.42 ms, including retrace) is such that successive six line swaths are contiguous.

BULK IMAGE FORMAT

The telemetered image data is converted to film copy using an electron beam recorder (EBR) in the ERTS NASA Data Processing Facility (NDPF) at GSFC. The EBR is in the bulk processing subsystem of the NDPF where the bulk of the data is converted to film copy. A 70 mm format has been established for the film copy produced by the EBR. In this 70 mm format a nominal square image 185.2 by 185.2 km (100 by 100 nautical miles) will be scaled to 55 by 55 mm. The maximum image area available is 60 by 60 mm (202 by 202 kilometers) and any image data falling outside this area is not recorded. The 70 mm transparencies recorded by the EBR are the master archival positives from which two 70 mm and one 9-1/2 inch negatives are made for all further copy work. The 9-1/2 (24.13 cm) inch enlargement are scaled 1:1,000,000 - a nominal 185.2 by 185.2 km (100 by 100 nautical mile) square image will be 7.3 by 7.3 inches (18.54 by 18.54 cm). The film imagery output of the bulk processing subsystem is geometrically corrected to the first order through the electron beam recorder image corrector (EBRIC). Systematic errors and spacecraft ephemeris data are taken into account for these corrections.

SPACECRAFT VELOCITY ORIENTATIONS

The RBV cameras detect a complete image frame simultaneously and it is the stored image which is scanned for video data; whereas the MSS detectors produce a continuous scan of a subsatellite swath. This basic difference in the production of scan line data leads to differences in the areas covered by corresponding image frames generated by the two systems. In order to define the ground area covered by an ERTS image, it must be noted that the ground scene contained in an image is located by the ground track and it is oriented with reference to the spacecraft velocity in the orbit plane. Due to the rotation of the earth, the direction of the subsatellite point velocity in the orbit plane is different from the direction of the ground track velocity as shown in Figure 1.

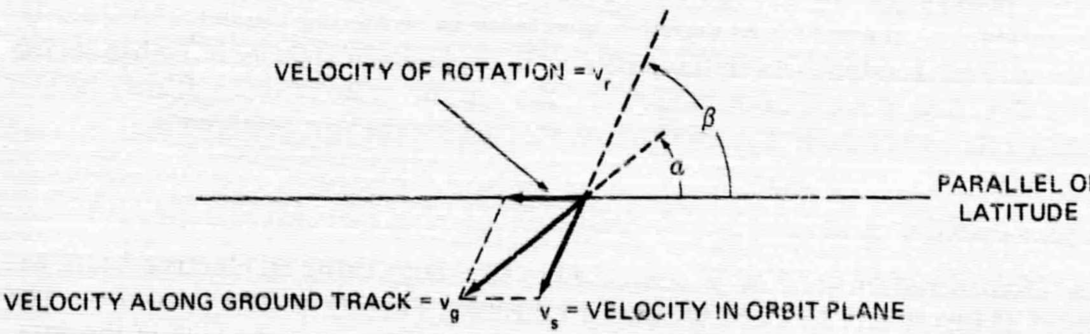


Figure 1. Difference in Direction of Ground Track and Orbit Velocities

The direction of the subsatellite point velocity in the orbit plane is defined by the angle β which is the angle between the subsatellite point track in the orbit plane and a parallel of latitude as shown in Figure 1. For a given latitude θ, the angle β is given by the equation

$$\cos\beta = \frac{\cos 81^\circ}{\cos\theta} \qquad (1)$$

The factor cos 81° accounts for the orbit inclination. It should be noted that the angle β is determined by the intersection of the orbit plane with the surface of the earth (spherical earth assumed here) and does not depend on the rotation of the earth.

On the other hand, the direction of the ground track velocity does depend on the rotation of the earth. The direction of the ground track velocity can be defined by the angle α which is the angle between the ground track and a parallel of latitude as shown in Figure 1. For a given latitude θ, the angle α is given by the equation

$$\tan \alpha = \frac{(\cos^2 \theta - \cos^2 81°)^{1/2}}{\cos 81° + \frac{V_r}{V_s} \cos^2 \theta} \tag{2}$$

V_s = Subsatellite point velocity in orbit plane

= 6.46 kilometers/second

V_r = Rotational velocity of a point on the equator

= 0.46 kilometers/second

The angle α is the satellite heading relative to a parallel of latitude.

Table 1 lists the calculated values of α, β, and the difference $\beta - \alpha$ as a function of the latitude θ. The maximum difference $\beta - \alpha = 4°$ occurs at the equator and

Table 1

Orbit Plane and Ground Track Directions

Latitude θ (degrees)	β (degrees)	α (degrees)	$\beta - \alpha$ (degrees)
0	81	77	4
30	79.6	76.1	3.5
45	77.2	74.3	2.9
60	71.8	69.8	2
81	0	0	0

the difference decreases with increasing latitude until it reaches the minimum value of zero at 81° latitude. At 81° latitude the orbit plane subsatellite track and the actual ground track are tangent to the parallel of latitude which results in $\beta = a = 0°$.

SPACECRAFT ATTITUDE

The location and orientation of the ground scene covered by an ERTS image also depend on the attitude of the spacecraft in its orbit. Using the coordinate axis of Figure 2 the three attitude angles are defined as follows:

OX is the spacecraft velocity vector and the roll axis.

OY is the pitch axis.

OZ is the yaw axis and extends upward from the earth.

OX and OZ define the orbit plane.

Positive roll rotates Y towards Z (Angle measured in YZ plane)

Positive pitch rotates Z towards X (Angle measured in XZ plane)

Positive yaw rotates X towards Y (Angle measured in XY plane)

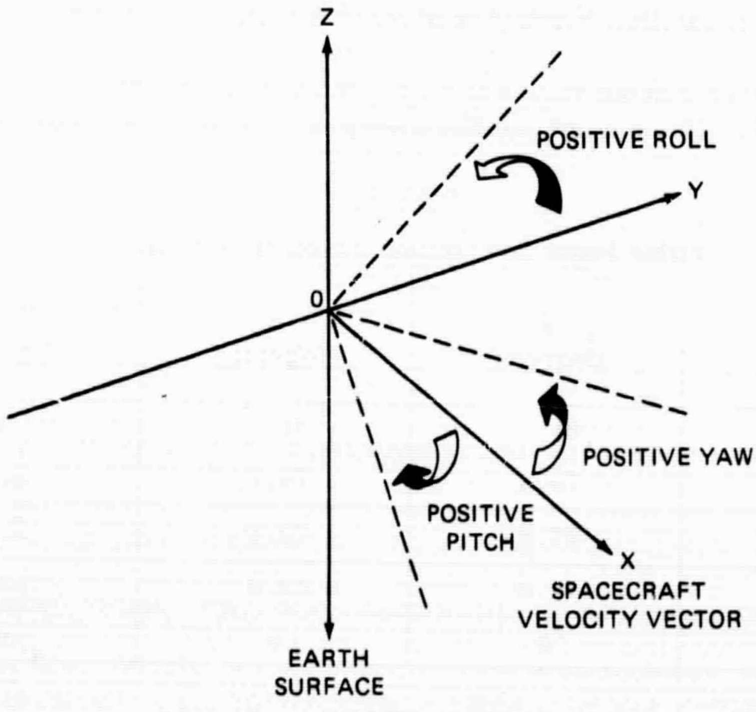


Figure 2. Satellite Attitude Angles

The maximum attitude variations specified for the ERTS satellite are 0.7 degree yaw, pitch, and roll with maximum rates of change of 0.4 degree per second. As of February 1971, the maximum variations expected are 0.4 degree pitch and roll, and 0.61 degree yaw with worst case rates of 0.01 degree per second and typical rates of 0.005 degree/second.

The optical axes of the three RBV cameras and the MSS detector are nominally aligned parallel to the spacecraft yaw axis. The scan lines generated by the sensor are nominally parallel to the pitch axis. Variations from this nominal case due to boresight errors will be discussed later. To simplify the discussion which follows we will first consider the case of perfect alignment and assume zero boresight errors.

SPACECRAFT ALTITUDE

The altitude of the spacecraft determines the size of the ground area subtended by the angular aperture of the sensor. The nominal RBV image of 185.2 by 185.2 km corresponds to the plane area subtended by an aperture 16.22° across the diagonal from an altitude of 918.6 km (496 nautical miles). The actual image size is proportional to the satellite altitude as shown by the curve in Figure 3. For example, at the specified nominal altitude of 911.8 km (492.35 nautical miles), the RBV scene will be 183.83 by 183.83 km. The spacecraft altitude is a function of latitude and orbit number.* At the equator the altitude varies roughly from 900 km to 917 km and the specified nominal altitude of 911.8 km is actually the average altitude at the equator. For any given orbit the altitude is a minimum at the equator and increases to a maximum of 931 km near 81 degrees latitude. At 30 degrees latitude the altitude will be between 911 and 920 km, and at 60 degrees latitude the altitude will range between 920 and 928 km. It should be noted that for latitudes above 30 degrees the altitude will never be as low as the specified nominal altitude of 911.8 km. For the remainder of our discussion we will assume an altitude of 918.6 km for the convenience of working with a nominal 185.2 by 185.2 km (100 by 100 nautical mile) RBV image. Since the size of an image and the ground displacement due to pitch and roll are proportional to the spacecraft altitude, the correction for different altitudes is straightforward. In any case, even for the extremes of maximum (930 km) and minimum (900 km) altitudes the corrections will be less than 2.0 per cent.

*Assuming a circular orbit, altitude variations are introduced by the oblateness of the earth and perturbing forces such as the gravity of earth, sun, and moon.

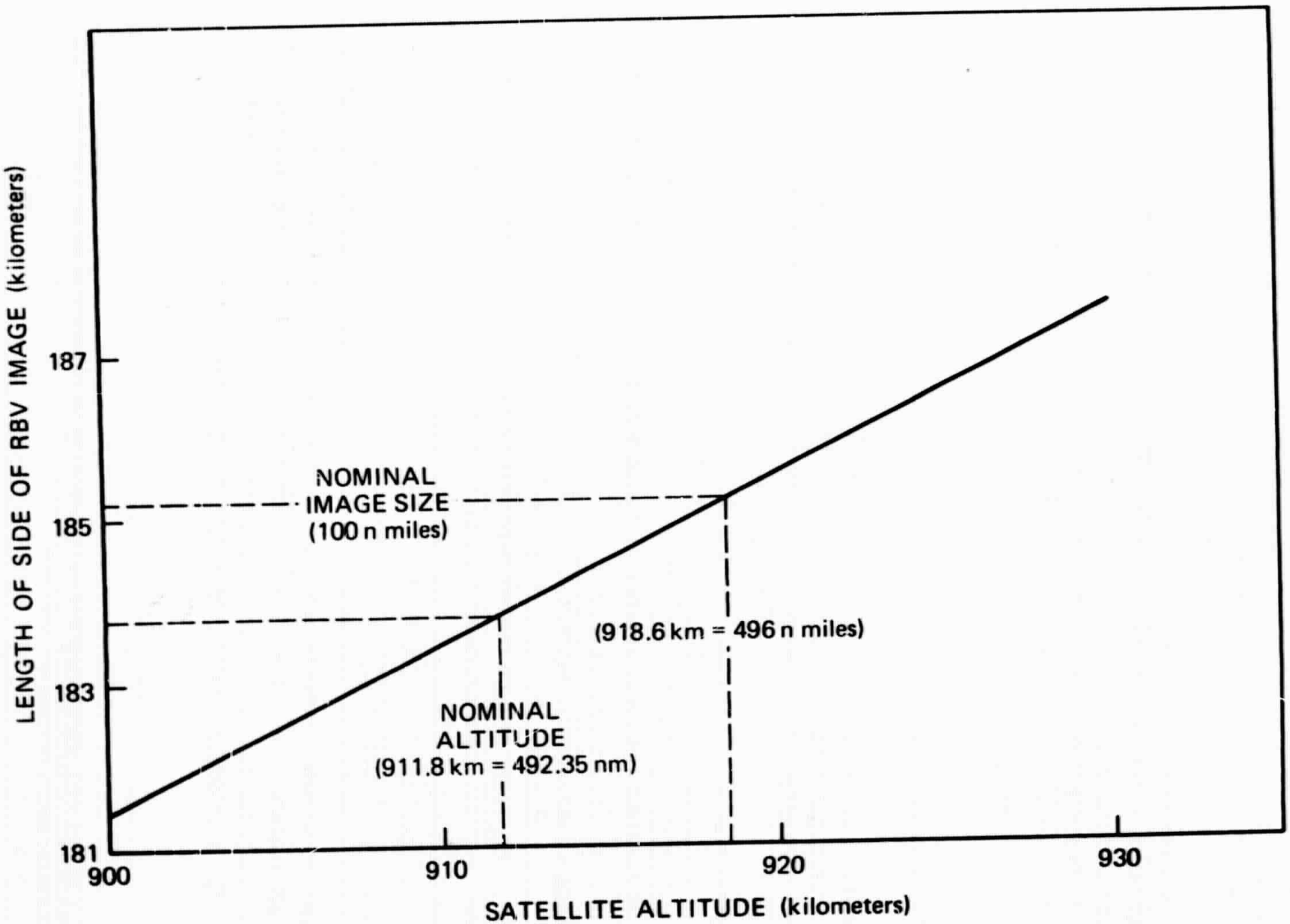


Figure 3. RBV Image Size as Function of Satellite Altitude

EARTH CURVATURE

As mentioned in the previous paragraph, the ground scene dimensions are based on the plane area subtended by the aperture angle of an RBV camera. Due to the curvature of the earth, the diagonal of the actual ground area information contained in an image is 0.37 kilometer greater than the diagonal of the nominal square image obtained with the flat-earth approximation. This effect of the earth curvature can be compensated to a great extent by proper adjustment of the image scale. The details of such adjustments will not be considered here and the flat-earth approximations will be used for the remainder of this study.

RBV IMAGES

The vertical axis of an RBV image will nominally coincide with the orbit plane at the time of exposure and the spacecraft velocity in the orbit plane will be directed toward the bottom of the image. This nominal case assumes zero attitude and boresight errors. For this case the orientation of an RBV axis with respect to east is given by the angle β as defined by (1). Figure 4 shows the orientation of an RBV image relative to the compass directions north and east at image center for the five values of latitude listed in Table 1.

Variations in the actual ground coverage of an RBV image are caused by changes in the attitude of the spacecraft relative to the direction of its velocity in the orbit plane. Since the image center is defined as the geometric extension of the spacecraft yaw attitude sensor axis to the Earth's surface, a yaw error simply rotates the RBV image area about its center. For the case of an RBV image with yaw angle Y at time of exposure the angle between the RBV vertical axis and the direction of east will be $\beta \pm Y$ as shown in Figure 5. Comparison of Figures 4 and 5 indicates that the RBV vertical axis will be at an angle Y with respect to the orbit plane and therefore it is only for the nominal case with $Y = 0$ that the vertical axis is parallel to the orbit plane.

From the definitions of pitch and roll given previously, it should be clear that pitch and roll involve rotations of the spacecraft yaw axis parallel and perpendicular to the orbit plane. Since image center lies on the extension of the yaw axis, pitch and roll produce displacements of image center from the nominal location at the subsatellite point. For the small angles of pitch and roll (0.7° maximum) the displacement of image center is approximately hA where h is the satellite altitude and A is the pitch or roll angle in radians. For the altitude of 918.6 km the displacement is 11.2 km for the specified maximum angle of 0.7° and is 6.4 km for the expected worst case of 0.4°. Displacement of the RBV image center implies that the ground area covered by the RBV image is shifted the appropriate distance relative to the nominal ground area centered on the subsatellite point.

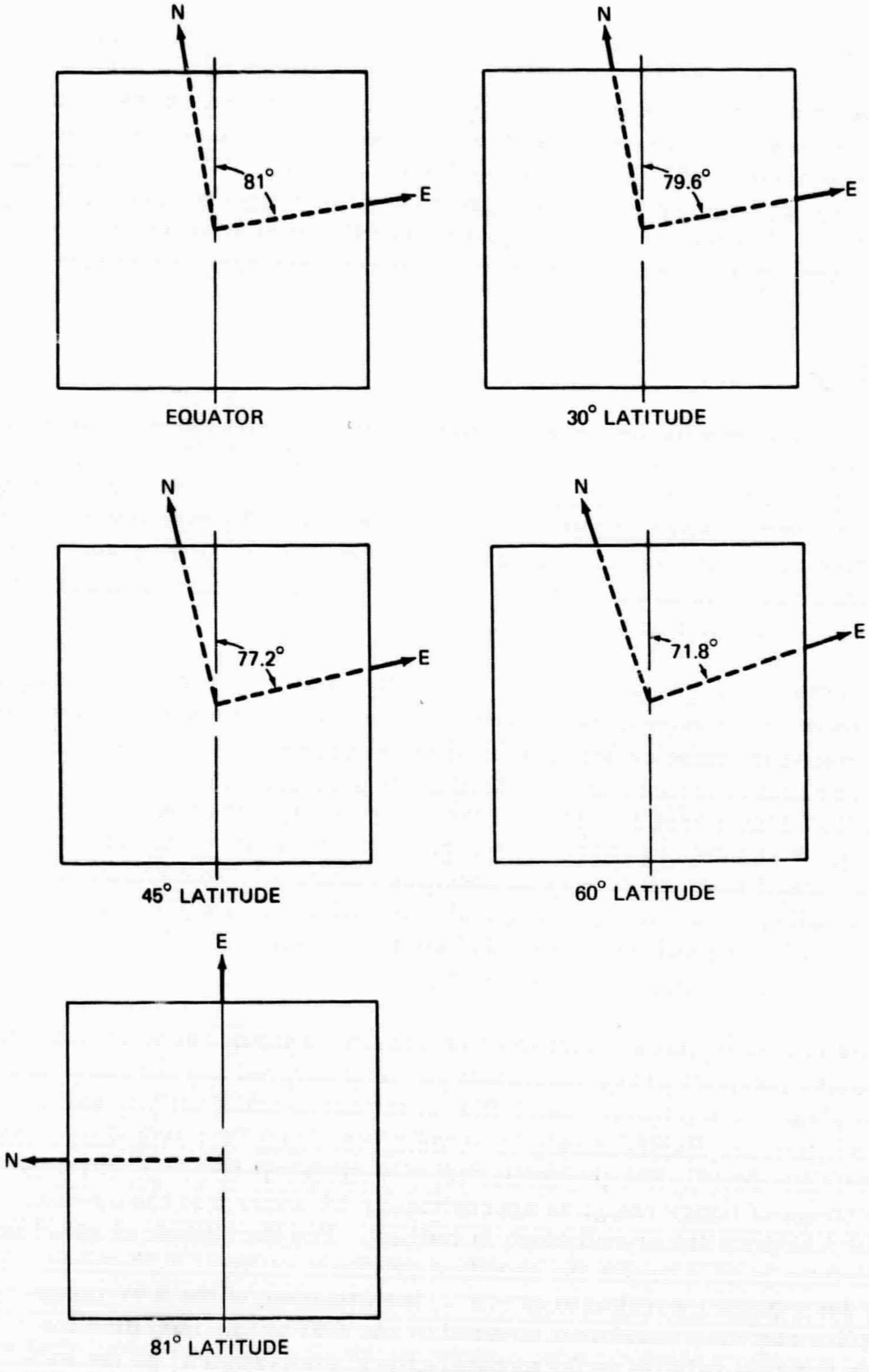


Figure 4. Orientation of RBV Images

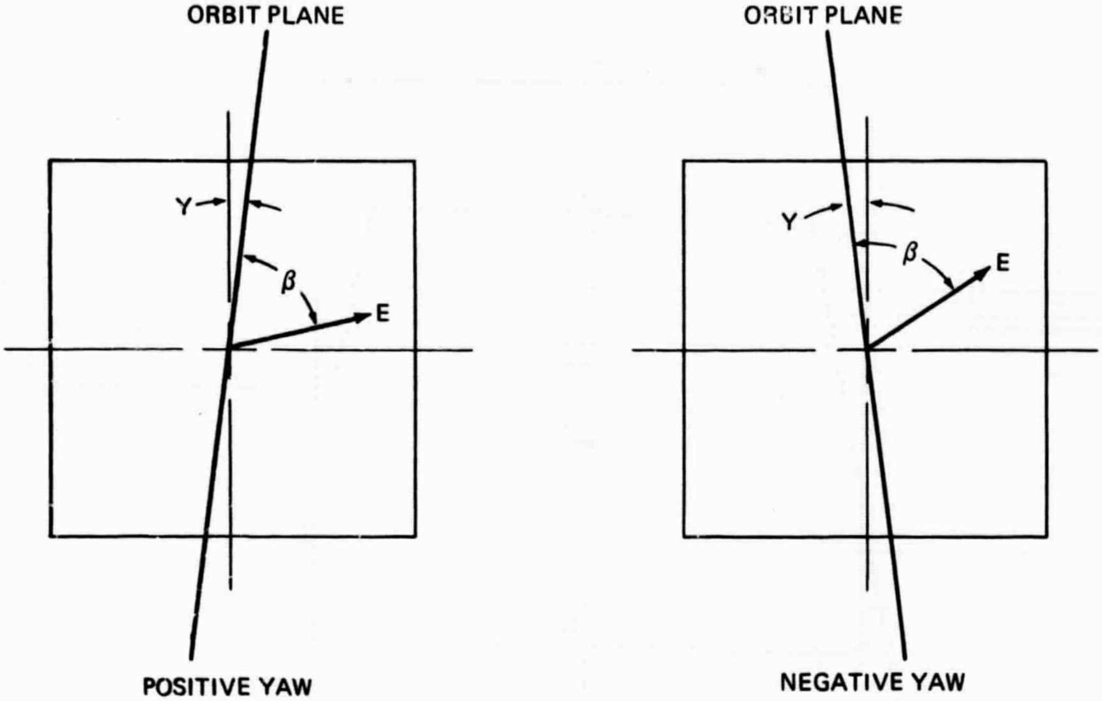
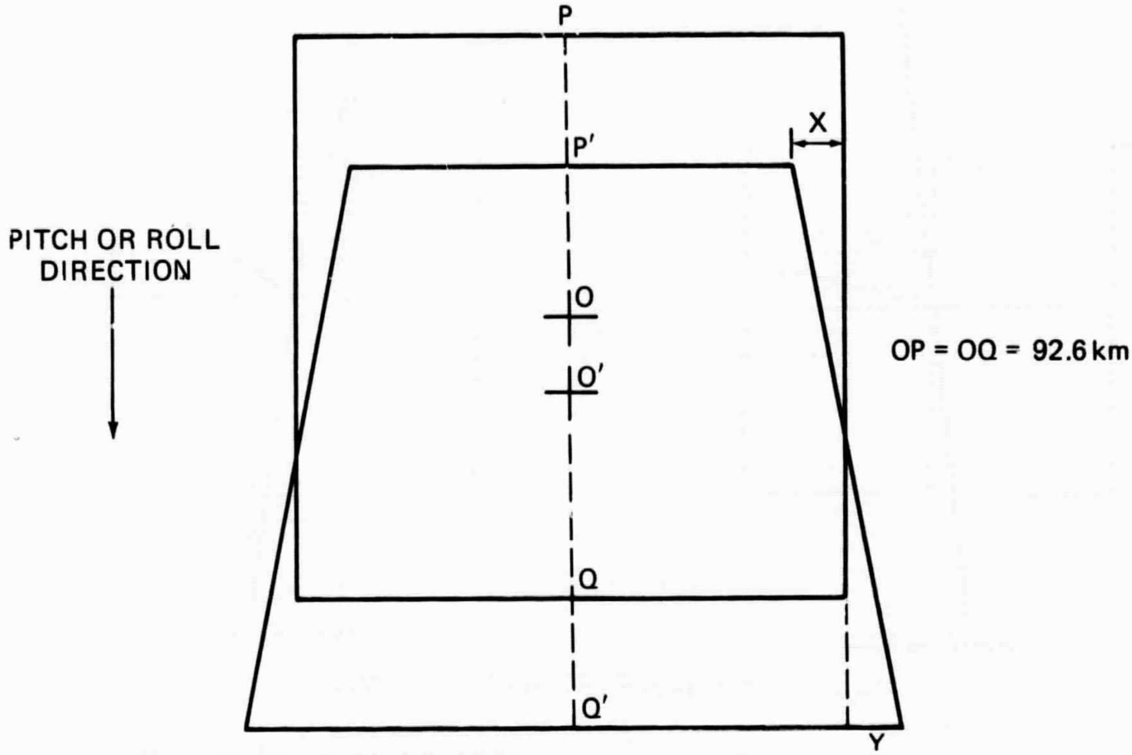


Figure 5. RBV Image Orientation with Yaw

A lesser effect known as keystoning also occurs when there is pitch or roll. This effect is diagrammed in Figure 6. The fixed aperture angle subtends a greater (lesser) line length as the distance from the satellite to the ground increases (decreases) due to the change in direction of the optical axis. As shown in Figure 6, the keystone effect produces changes in the boundaries of the ground coverage of an RBV image which are less than 0.17 km for the 0.7 degree pitch and roll (specified maximum) and less than 0.13 km for 0.4 degree pitch and roll (expected maximum). These errors are neglected in the bulk processing of RBV images.

From this discussion it is apparent that in regard to RBV images, attitude variations will have no appreciable effect on the shape of image boundaries. The actual ground area included in an image frame will be displaced from the nominal subsatellite scene by a maximum of $6.4\sqrt{2}$ km due to pitch and roll and will be rotated a maximum of 0.61 degree from nominal due to yaw about image center. Except for possible systematic distortions by the imaging components and the 2.0 per cent variations in size due to altitude changes, RBV images will be 185.2 by 185.2 km square.



PITCH OR ROLL	O O'	X	Y	O' P'	O' Q'
0.7°	11.2	0.15	0.17	92.45	92.77
0.4°	6.4	0.08	0.09	92.49	92.73

(All Lengths in Kilometers)

Figure 6. Keystone Effect of Pitch or Roll

MSS IMAGES

The MSS is continuously scanning as compared to the frame by frame detection of the RBV cameras and therefore detects a continuous ground swath 185.2 km wide. This continuous swath of MSS data is framed into images comparable to the RBV images when printed by the EBR. The center of an MSS image frame is chosen to coincide with the RBV image center for the corresponding ground scene. The start and end of an MSS image frame are nominally defined by the scan lines 13.8 seconds before and after image center respectively. Thus approximately 27.6 seconds of MSS data is contained in each image frame.

Since the MSS mirror nominally scans orthogonal to the spacecraft orbit plane, the MSS scan lines will be approximately parallel to the RBV scan lines. This approximation assumes that parallels of latitude are straight lines in an ERTS image and that the angles α and β may be considered constant across an ERTS image. Both of these assumptions provide good approximations near the equator but introduce errors which may be appreciable at the higher latitudes. Figure 7 shows the relative location of the MSS and RBV scan lines for the nominal

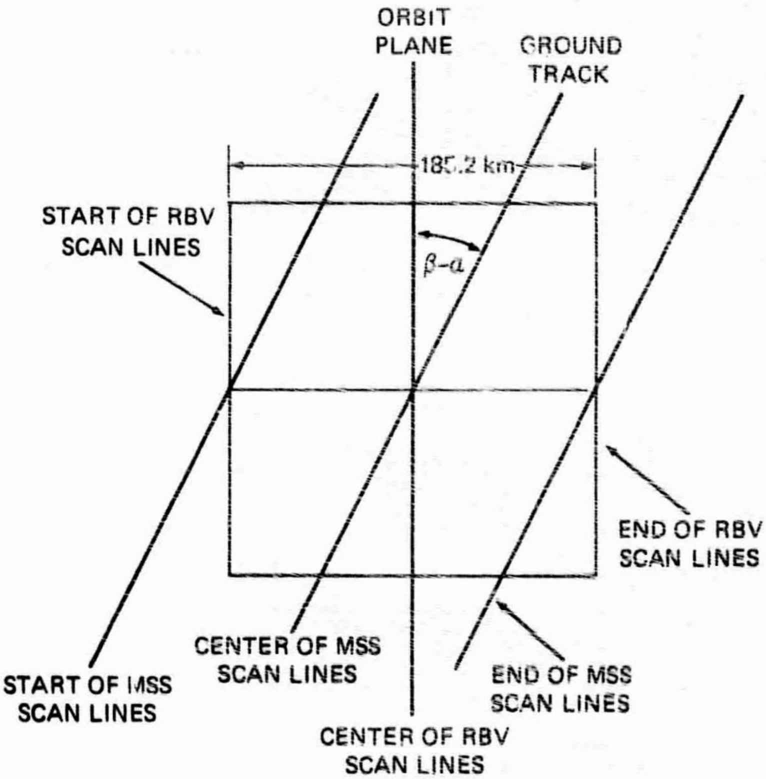


Figure 7. Nominal Shift of MSS Lines Relative to RBV

case. The center of each six line scan swath of MSS data is nominally located on the ground track of the satellite. It should be noted that this centering of MSS scan lines is different from that of the RBV where the scan lines are nominally centered on the orbit plane at the time of exposure. Due to spacecraft motion during the MSS scan time, the MSS lines actually scan the ground at an angle of approximately 0.06 degree relative to the nominal orthogonal direction. The MSS images will be recorded with scan lines assumed orthogonal to the orbit plane since this tilt of 0.06 degree has little effect on image geometry.

As seen in Figure 7, an MSS image frame will cover a ground area skewed with respect to the corresponding RBV image. This effect is due to the rotation of the earth and the skew is given by the angle ($\beta - \alpha$) under the assumptions discussed previously. Referring back to Table 1 and equations (1) and (2), it is seen that the skew angle is a maximum of 4 degrees at the equator and decreases as the latitude increases. The geometry for the location of the MSS boundary scan line center with respect to image center is shown in Figure 8. As mentioned previously the first and last MSS scan lines are 13.8 seconds from image

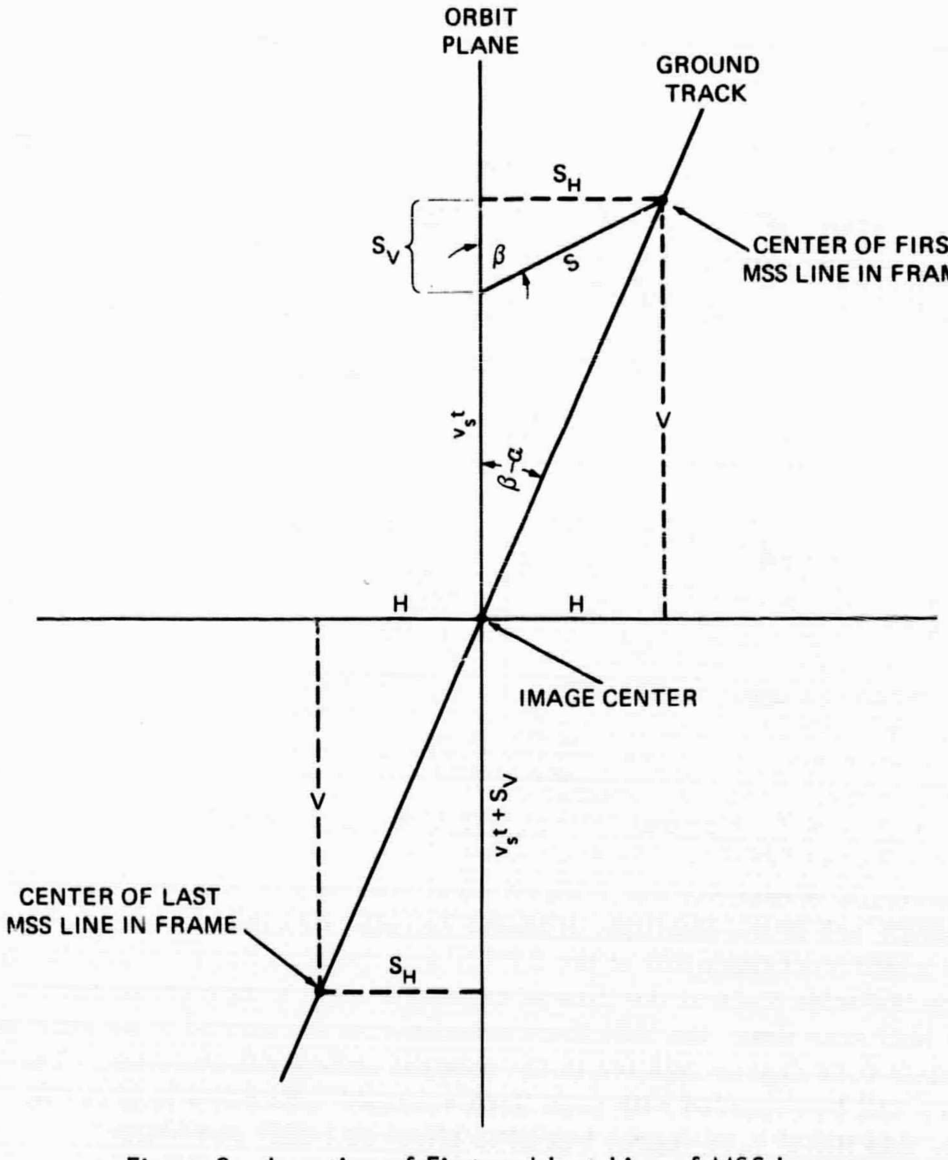


Figure 8. Location of First and Last Line of MSS Image

center. In this time the spacecraft will move a distance $v_s t$ in the orbit plane and the earth will rotate the distance $S = v_r t \cos\theta$ as shown in Figure 8. The displacement S is in the direction of east and is therefore at the angle β with respect to the orbit plane. The location of the MSS end line center for a nominal image (zero attitude errors) can be defined in terms of the horizontal (H) and vertical (V) displacement relative to image center which are given by the expressions

$$H = S_H = S \sin\beta \tag{3}$$

$$V = S_v + v_s t = S \cos\beta + v_s t \tag{4}$$

Using $t = 13.8$ seconds with the previously given values of $v_s = 6.46$ km per second and $v_r = 0.46$ km per second and (1) equations (3) and (4) can be rewritten as

$$H = 6.39 \cos\beta \sin\beta \text{ kilometers} \tag{3}$$

$$V = 6.39 \cos 81^\circ + 89.14 = 90.14 \text{ kilometers} \tag{4}$$

If we define the vertical size of an MSS image as the vertical spacing between end line centers the vertical size of a nominal MSS image is $2V = 180.28$ km (97.34 n miles). It should be noted that the vertical size of a nominal MSS image is independent of the satellite altitude (except through the dependence of satellite velocity on altitude). In contrast to an RBV image whose ground coverage changes in both the horizontal and vertical directions, as the altitude varies, the MSS image coverage will only vary horizontally. At this point we can reconsider the two assumptions discussed earlier. First, if the parallels of latitude are not imaged as straight lines the displacement S is measured along a curve and the projection into vertical and horizontal components will be a poorer approximation the greater the curvature. If the angles α and β are not constant over an image frame the ground track will appear as a curved line and/or the difference in the angle β can change the vertical and horizontal components of the displacement S. As an example of the order of magnitude of angle changes - the angle β varies by almost one degree along the orbit plane through the center of an image located at 60 degrees latitude.

The effects of attitude errors on the boundaries of an MSS image frame can be considered in two parts - the effects due to the attitude at the time corresponding to image center and the effects due to changes in attitude from the center to the time of the boundary scan lines. The pitch and roll at the time of image center will displace the image center from the nominal location on the orbit plane. Since the MSS and RBV image frames have the same center, the worst case ground displacements of the MSS image center will be the same as those previously given for the RBV image. Spacecraft yaw at image center does not have the same effect on MSS image coverage as it does on RBV image coverage because of the difference in scanning. As we have shown, yaw at the time of image center rotates the entire RBV image about its center. In the case of an MSS image, the entire image is not rotated by yaw - each scan line (more correctly, each six line set of scan lines) is rotated about its center by the value of yaw at the time of the respective line. In the case of yaw at image center Figure 8 is still correct as a representation of the orientation of an MSS image with respect to the orbit plane. For a comparison of MSS and RBV ground coverage, it will be convenient to continue our discussion using the vertical axis of the RBV image as a reference. Figure 9 shows the geometry for relative orientation of

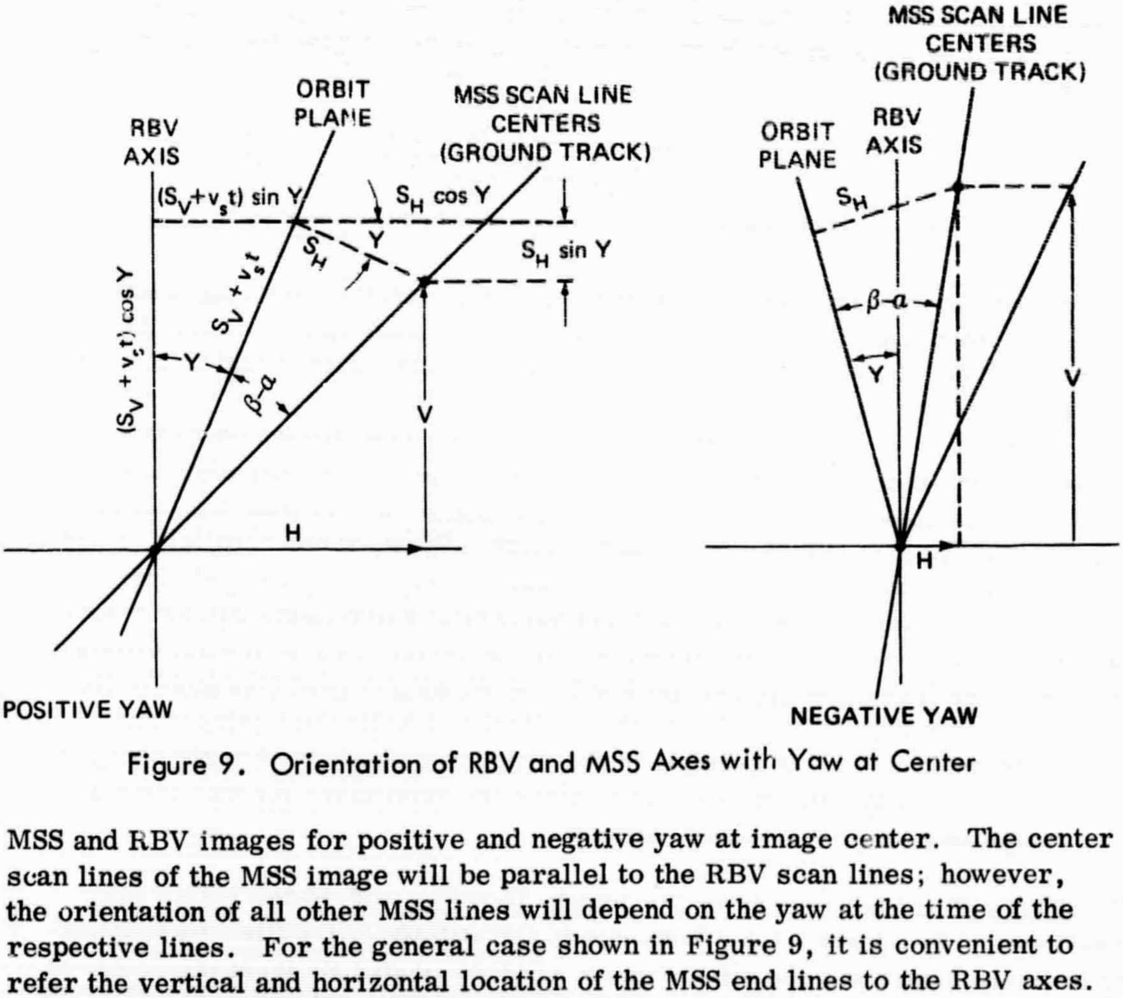


Figure 9. Orientation of RBV and MSS Axes with Yaw at Center

MSS and RBV images for positive and negative yaw at image center. The center scan lines of the MSS image will be parallel to the RBV scan lines; however, the orientation of all other MSS lines will depend on the yaw at the time of the respective lines. For the general case shown in Figure 9, it is convenient to refer the vertical and horizontal location of the MSS end lines to the RBV axes. From the geometry of Figure 9, the vertical (V) and horizontal (H) coordinates of the MSS end line centers are given in kilometers by the equations

$$H = S_H \cos Y + (S_v + v_s t) \sin Y \qquad (5)$$

$$V = (S_v + v_s t) \cos Y - S_H \sin Y \qquad (6)$$

Equations (5) and (6) reduce to equations (2) and (3) when the yaw angle Y is zero. For the small angles of yaw allowed (0.7° maximum), cos Y is approximately one (cos Y > 0.99993) and sin Y is given to a good approximation by 0.01745 Y where Y is measured in degrees (or sin Y ~ Y if Y is in radians).

Using these small angle approximations and the values of S_H, S_v, and $v_s t$ as previously defined, equations (5) and (6) can be rewritten as

$$H = 6.39 \cos\theta \sin\beta + 1.57 Y \tag{5}$$

$$V = 90.14 - 0.11 Y \cos\theta \sin\beta \tag{6}$$

The MSS end line can also be displaced by satellite pitch and roll. Since the pitch and roll at image center is clearly accounted for by the ground location of the image, only the difference in pitch and roll from the values at image center remain to be considered. As discussed for the RBV image the ground displacement due to pitch and roll is approximately hA where h is the altitude and A is the pitch or roll angle in radians. The displacement of MSS end lines due to pitch and roll are therefore 16.04 P and 16.04 R where P and R (degrees) are the difference in pitch and roll angles from the values at image center (h = 918.6 km). Noting that pitch displacement are in the same direction as S_v and roll displacements are in the direction of S_H, these corrections can be incorporated into equations (5) and (6) to obtain the general results.

$$H = 16.04 R + 6.39 \cos\theta \sin\beta + (1.57 + 0.28 P) Y \tag{7}$$

$$V = 90.14 + 16.04 P - (0.11 \cos\theta \sin\beta + 0.28 R) Y \tag{8}$$

Equations (7) and (8) define the position of the end lines of an MSS image relative to image center in units of kilometers of ground coverage in terms of the angles θ, β, Y, R, and P. It shall be noted that Y is the yaw angle at image center, whereas P and R are the difference in pitch and roll from image center to end line. Figure 10 shows the geometric significance of each term in equations (7) and (8) (angle and scale exaggerated for clarity).

For numerical consideration of worst case displacements due to changes in pitch and roll during an MSS frame, we will assume constant worst case error rates for the full 13.8 seconds from end line to image center. For the three cases of

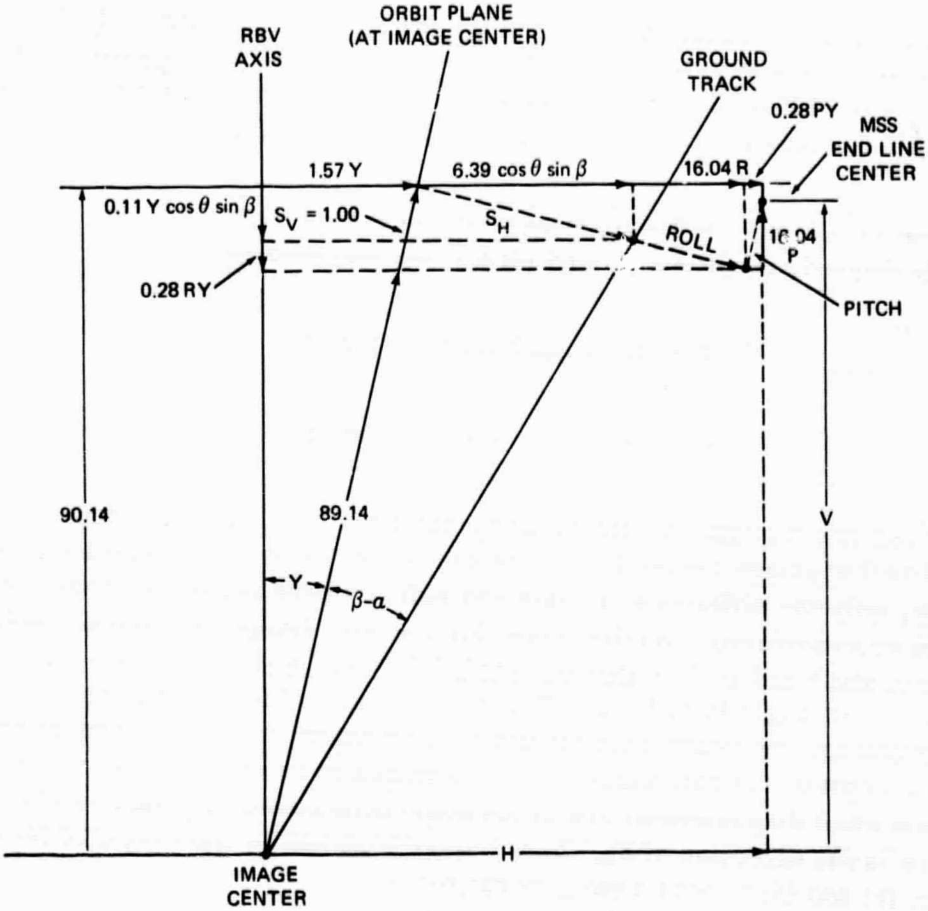


Figure 10. Geometry for Determination of V and H

worst case error rates previously given, the worst case pitch and roll differences from center to end line are listed here.

Error Rate (degree/second)		Maximum Pitch and Roll Change in 13.8 Seconds (degree)
Specified Maximum	0.04	0.55
Expected Maximum	0.01	0.14
Typical	0.005	0.07

The terms 0.28 PY and 0.28 RY in equations (7) and (8) have maximum values of 0.107 km for specified maximums, 0.004 km for expected maximums, and 0.0007 km for typical rates. The term $0.11 \cos\theta \ \sin\beta$ Y in equation (8) has a maximum value of 0.074 km at the equator and decreases as the latitude θ increases. Since these terms represent maximum variations of less than 0.1 km in H and V, we can simplify equations (7) and (8) to

$$H = 16.04R + 6.39 \cos\theta \sin\beta + 1.57Y \tag{9}$$

$$V = 90.14 + 16.04P \tag{10}$$

The vertical position V of the MSS end line, as given by (10), depends only on the difference in pitch P. Table 2 lists the values of V for worst case pitch

Table 2

Vertical Position of MSS Start Scan Line

Pitch Difference P, degree	Vertical Position of MSS Start Line V, kilometers	Vertical Size 2 V, kilometers
0.55	98.95	197.9
0.14	92.34	184.7
0.07	91.25	182.5
0	90.14	180.3
-0.07	89.03	178.1
-0.14	87.93	175.9
-0.55	81.32	162.6

difference. The vertical size of an MSS image as given by 2 V in Table 2 assumes constant worst case pitch rates from start to end of the MSS image frame. The horizontal position of the MSS end line, as given by (9), is a function of latitude θ, yaw at image center Y, and the difference in roll R. Table 3 lists the values of H for worst case combinations of R and Y for θ = 0, 30, 45, and 60 degrees latitude.

Finally, the effect of differences in yaw from image center to end line will be considered. Changes in yaw during the MSS image frame time will produce a

Table 3

Horizontal Position of MSS Start Scan Line

Yaw at Center Y, degree	Roll Difference R, degree	Horizontal Position H, kilometers			
		$\theta = 0$	$\theta = 30°$	$\theta = 45°$	$\theta = 60°$
0	0.55	15.13	14.26	13.22	11.85
	0.14	8.52	7.65	6.61	5.24
	0.07	7.43	6.56	5.52	4.15
	0	6.32	5.44	4.41	3.04
	-0.07	5.20	4.33	3.30	1.93
	-0.14	4.11	3.24	2.20	0.83
	-0.55	-2.50	-3.37	-4.41	-5.78
+0.61	0.14	9.50	8.63	7.59	6.22
	0.07	8.41	7.54	6.50	5.13
	0	7.28	6.41	5.37	4.00
-0.61	0	5.35	4.48	3.44	2.07
	-0.07	4.22	3.35	2.32	0.94
	-0.14	3.13	2.26	1.22	-0.15
+0.7	0.55	16.37	15.50	14.46	13.09
	0.14	9.67	8.80	7.76	6.39
	0.07	8.57	7.70	6.67	5.30
	0	7.45	6.57	5.54	4.17
-0.7	0	5.19	4.32	3.28	1.91
	-0.07	4.06	3.19	2.15	0.78
	-0.14	2.96	2.09	1.06	-0.31
	-0.55	-3.74	-4.61	-5.65	-7.02

rotation of each MSS scan line about its respective center. Since the rotation will vary with yaw, the MSS scan lines will no longer be parallel to each other. For worst case rotation, the maximum difference in yaw (ΔY) from image center to MSS end line will be given by the angles 0.55, 0.14, and 0.07 degree previously listed for worst case pitch and roll changes. These angles also apply to the yaw since the maximum rates are the same for all three attitude angles. The displacement D of the scan line ends will be given by $D = 92.6\ (0.0175)\ \Delta Y$ which gives 0.89, 0.22, and 0.11km for the three cases of attitude rates being considered.

COMPARISON OF MSS AND RBV IMAGES

The relation between the ground coverage of an RBV image and an MSS image of the same scene is summarized in Figure 11 which shows the three major parameters V, H, and D. Figure 11 also indicates the possible clipping of MSS

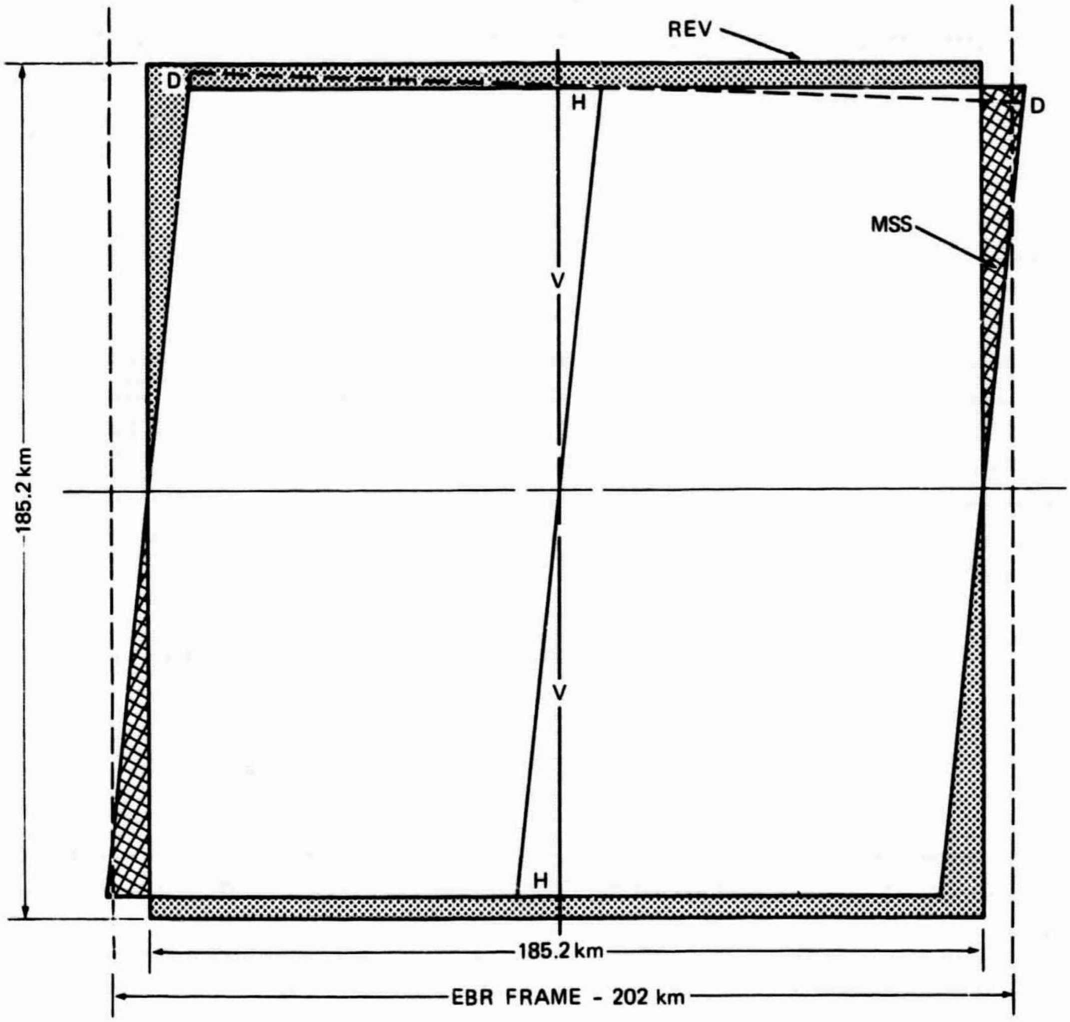


Figure 11. Comparison of MSS and RBV Ground Coverage

corners due to the 60 mm frame limit of the EBR which restricts ground coverage to a maximum of 202 km. This maximum frame size does not clip MSS images unless H is greater than 8.4 km. Examination of Table 3 indicates that clipping of MSS images will occur only for a few extreme cases. For the worst case expected (+0.61 degree yaw and +0.14 degree roll) at the equator, H will be 9.5 km and 1.1 km will be clipped from the upper right-hand and/or lower left-hand corners.

Using Figure 11 and Tables 2 and 3 we can estimate the percentage of MSS image area which will not be included in the corresponding RBV image. The triangular cross-hatched areas in Figure 11 represent MSS ground coverage outside the RBV image. The area of each triangular area will be $\frac{HV}{2}$. The combined area of the two triangles is HV and the total MSS image area is 370.4 V, therefore, the percentage of MSS image area not included in the RBV coverage is

$$\% \text{ MSS area not in RBV} = \frac{HV}{370.4\,V} \times 100 = 0.27\,H \tag{11}$$

Using the minimum value of H = 0 and the expected maximum value of H = 9.50, it is found that from zero to 2.6 per cent of MSS image area will not be covered by the corresponding RBV image.

We can also make the reverse comparison and determine what percentage of the RBV image area will not be included in the corresponding MSS scene. The shaded area in Figure 11 represents the portion of the RBV image not covered by the MSS. This area is made up of two triangles identical to those considered in the previous case plus bands at the top and bottom due to the difference in the vertical size of the images. The percentage of RBV image area not covered by the corresponding MSS image is

$$\begin{aligned} \% \text{ RBV area not in MSS} &= \frac{HV + 370.4\,(92.6 - V)}{(185.2)^2} \times 100 \\ &= 100 - V\,(1.08 - .003\,H) \end{aligned} \tag{12}$$

Using the expected extremes of V and H, we find the percentage of RBV image area not covered by the corresponding MSS image will range from 0.3 to 7.5 per cent.

BORESIGHT ERRORS

Throughout our discussion to this point, we have assumed that the RBV cameras and the MSS telescope system are perfectly aligned with the spacecraft attitude sensor yaw axis. The three RBV cameras are to be aligned with respect to the camera baseplate so that the three camera axes are within a 14 arc minute square pyramid. The camera baseplate is then aligned within 6 arc minutes relative to the spacecraft axis. Thus if we assume the worst case alignment of an RBV camera to baseplate is 14 arc minutes and take the maximum boresight alignment error to be the square root of the sum of the squares (RSS) of the two alignment errors, the maximum boresight error will be 15.23 arc minutes or 0.25 degree. This misalignment of an RBV camera relative to the spacecraft axis will cause a shift in the ground coverage similar to the pitch or roll effect previously discussed. For the altitude of 918.6 kilometers, an 0.25 degree pointing error will produce a shift in the location of the ground scene of 4.0 kilometers. Since the center of the ERTS image format is defined in terms of the spacecraft yaw axis, this shift of the ground scene due to boresight error will appear as an actual shift of the square RBV image within the EBR image frame. The direction of the boresight shift will coincide with the direction of RBV camera misalignment.

The same type of shift will occur in MSS image coverage where the maximum boresight errors are expected to be within 0.1 degree (1.59 kilometers) pitch and roll or 2.22 kilometers (RSS) in the resultant direction of misalignment. The relative displacement of MSS image center with respect to RBV image center can be as much as 6.22 kilometers for the extreme case of maximum misalignment in opposite direction with a maximum RSS value of 4.57 kilometers. The definition of format center can be adjusted to partially compensate for boresight error. For example if all detectors are misaligned in the same direction, the offset of images within the image frame can be minimized by defining format center to fall on an axis at the average boresight angle with respect to the yaw axis.

The separate alignment of the RBV and MSS system in yaw relative to spacecraft axis is expected to be within 0.1 degree. The three RBV cameras are to be aligned in yaw with respect to each other so that the ends of the center scan lines are within two scan line widths of each other. If this is accomplished the yaw between RBV images will be negligible. The yaw misalignment of the RBV camera with respect to the spacecraft will add to the rotation of image coverage due to spacecraft yaw. Depending on the direction of yaw, a 0.1 degree boresight yaw will change the expected worst case rotation of ±0.61 degree to -0.51 and +0.71 or -0.71 and +0.51 degrees. As in our previous considerations, the boresight yaw of the MSS does not rotate the MSS image. The boresight yaw will rotate all scan lines the same angle about their respective centers. Thus if the spacecraft yaw does not change during a frame time, all MSS lines will be parallel to each other. In this case the relative angle between the MSS scan lines and RBV scan lines will be the resultant of the two boresight yaw angles. This angle may be from zero (equal boresight yaw in same direction) to a maximum of ±0.2 degree (0.1 maximum in opposite directions).

We will not try to determine percentage of image areas not common to both systems when boresight errors are non-zero. The percentages will be very much dependent on the directions of misalignment and any attempt to pick expected directions would be quite arbitrary. Since there is no capability to shim the MSS for fine corrections in boresight yaw alignment or to shim the RBV camera system for boresight roll alignment, it would appear that the boresight alignment will be poorest in these respective attitudes. Any special case of boresight error values and directions can be accounted for by adjusting the location and orientation of the image boundaries of Figure 11 in accordance with the effects discussed here.